Special Report

Design and Construction of Linn Cove Viaduct

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The Blue Ridge Parkway, owned by the United States National Park Services (NPS), is a unique transportation/recreation network. Built along the crest of the beautiful Blue Ridge Mountains in North Carolina, the 469 mile (755 km) long highway attracts millions of vacationers each year with its beautiful scenery and facilities for camping, hiking and picnicking.

Through the years the NPS has made every effort to preserve the natural beauty of the roadway and to provide access to adjacent areas with parking areas and nature trails. All highway construction is in accordance with the "park concept." For instance, fill must be placed and granite clad retaining walls built before the side of a mountain can be cut. All bridges are built with stone-clad curbs and wingwalls to blend with the surrounding mountain landscape. Bridges must also have open handrails so visitors will have an unobstructed view as they journey through the 479 mile (755 km) park.

Construction of the Parkway began in 1933 and was completed in the late 1950's with one exception: a 5-mile (8 km) length around privately owned Grandfather Mountain, which is one of the leading tourist attractions in North Carolina. The National Park Service had settled numerous location and right-of-way problems through the years, but none approached the magnitude of that centered on Grandfather Mountain.

The owner of Grandfather Mountain was insistent that construction of the Parkway must not harm or be obtrusive to the natural scenic beauty found there. Since the owner shared the same philosophy, the Federal Highway Administration (FHWA), which supplies engineering services for the Parkway, studied alignments and alternate routes

Several innovative design and construction techniques were used to build the Linn Cove Viaduct — a 1243 ft (379 m) long, S-shaped precast prestressed segmental concrete bridge — situated in one of the most scenically beautiful regions of the United States.


Fig. 1. Finished view of the Linn Cove Viaduct set against the beautifully rugged Blue Ridge Mountains.

for approximately 10 years.

Finally, a route which could not be seen from the mountain top was chosen around the eastern mountainside. To minimize construction damage to the area, the roadway alignment was raised above the mountainside by use of a viaduct structure.

Since building the viaduct structure by conventional methods of bridge construction would have done irreparable damage to the environmentally sensitive area, the search for an acceptable construction method became a challenging engineering problem.

DESIGN

The site within the limits of the Linn Cove Viaduct (Fig. 1) is a rugged and steeply sloped terrain with relatively heavy ground vegetation and boulder out-croppings. A natural stream crosses the bridge near the northern end. The scenic location, with its protruding boulders and the requirement for their protection and preservation, was the major factor to be considered in the design. Although rock existed throughout the site, it generally occurred below a relatively shallow overburden of soil surfaced with decomposed vegetation.

The structure proposed for this project was a precast post-tensioned segmental concrete box superstructure, eight spans in length with both horizontal and vertical curvature conforming to the natural topography. Progressing from south to north, the spans are 98.5, 163 ft (30, 48 m), four at 180, 163 and 98.5 ft (55, 50 and 30 m) in length. Each span is comprised of 9 ft (2.7 m) deep single cell boxes of 8.5 ft (2.6 m) nominal length located between 5 ft (1.5 m) long pier segments.

The Linn Cove Viaduct is probably one of the most complex bridges ever built; certainly, it must be the most complicated concrete segmental bridge ever constructed. Three major factors contribute to its complexity: environmental constraints and inaccessibility of the site and the vertical and horizontal alignment.

The bridge was literally built on the side of a mountain which had to remain in its natural state. There was only one

Fig. 2. Construction overview of Linn Cove Viaduct. This bridge is the first segmental structure in the United States to incorporate progressive placing erection.

way in or out, namely, over the completed portion of the bridge. The horizontal alignment includes spiral curves going into circular curves with radii as small as 250 ft (76 m) and with curvature in two directions, which gives the bridge its S shape (Fig. 2). A small portion of the bridge is on a horizontal tangent. The superelevation goes from a full 10 percent in one direction to a full 10 percent in the other direction in 180 ft (55 m) transitions and part way back again within the length of the bridge.

No two of the 153 superstructure segments have the same dimensions, and only one of the segments in the entire bridge is straight. When the vertical curve and tangential alignment are considered, the Linn Cove Viaduct includes almost every kind of alignment geometry used in highway construction.

The foundations consist of cast-in-place abutments at each end and seven intermediate precast segmental box piers bearing on 20 ft (6.1 m) diameter footings. Both the abutments and pier footings are supported on reinforced 9 in. (229 mm) diameter microshafts drilled into the underlying rock formations.

The bridge is 1243 ft (379 m) in overall length with a curb-to-curb roadway width of 35 ft (11 m). The final roadway surface is a 2 in. (51 mm) bituminous overlay with waterproofing membrane.

The structure was designed in 1979 in accordance with the AASHTO Standard Specifications for Highway Bridges (Twelth Edition 1977) except for those design and construction techniques particular to post-tensioned segmental construction. All superstructure and substructure precast segments were designed for a 28-day concrete strength of 6000 psi (41 MPa) with 4000 psi (28 MPa) specified for release of the forms. In addition to the longitudinal post-tensioning tendons, the top slab was designed to be transversely post-tensioned. All permanent post-tensioning was done with ½ in. (13 mm) diameter, 270 ksi (1863 MPa), low relaxation strand tendons.

To minimize the environmental impact on the construction site, the major portion of the bridge was to be built without the use of access roads. The only permitted construction road was from the south abutment of the second pier, a distance of approximately 260 ft (79 m). From this pier to the end of the bridge, the construction was to be from the previously completed portion of the deck.

No trees other than ones directly beneath the bridge were allowed to be cut. Each tree had to be evaluated separately and approved for cutting. All foliage adjacent to the bridge had to be protected

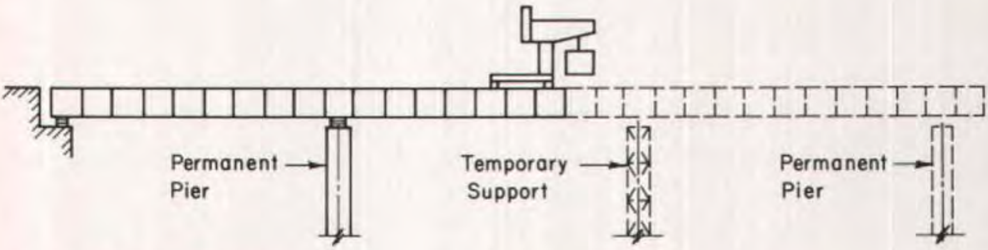

Fig. 3. Schematic view of the progressive placing erection method.

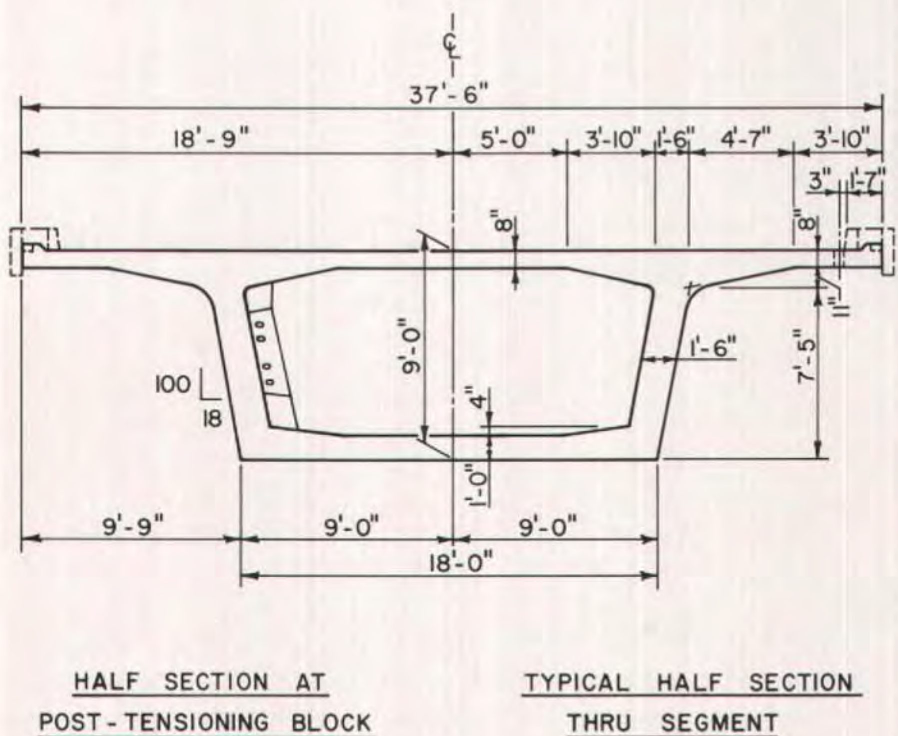

Fig. 4. Typical cross section of precast segment. The webs and bottom slab were thickened to carry the stresses due to the extreme curvature. Both temporary and permanent post-tensioning tendons were anchored at the intermediate stiffeners shown on the left side of the drawing.

by a silt fence located along the entire length of the bridge. Any construction debris on the outside of the silt fence had to be immediately retrieved.

None of the boulders could be defaced during construction, except in instances of rock bolting. The boulders were covered to prevent concrete, grout or epoxy stains. Any extraneous material on the boulders was immediately cleaned off.

The streams flowing across the bridge alignment were protected from siltation or other contamination. Water quality was constantly monitored.

Because of the severe environmental restrictions, the bridge could not be constructed by conventional methods and a system was devised in the design to construct it from the top. This required a progressive scheme which enabled segments of the bridge to be transported across the previously built deck and assembled into final position.

Precast concrete was chosen over cast-in-place segments because the region has a relatively short construction season. By choosing precast concrete, production of the segments could continue during the winter. Additionally, the precast segments were made under plant-controlled conditions which led to high quality concrete.

The progressive scheme (shown in Fig. 3) is considered feasible and structurally satisfactory for span ranges of from 150 to 200 ft (46 to 61 m). For these span lengths, a constant depth box girder has proven to be the most economical. After visits to the site and analysis of the possible locations of piers and temporary supports, the maximum span length was established at 180 ft (55 m). Spans were determined after locating piers to avoid the natural out-croppings of rock.

Typical box girder bridges have been built with span-to-depth ratios of 18 to 25. Structural aesthetics are generally more pleasing through the use of higher span-to-depth ratios. Considering the beautiful site of Linn Cove, it was decided to use a span-to-depth ratio of 22 to provide a graceful structure. However, after analysis of this cross section, it was decided to increase the depth of the box and the web thicknesses because the shallower depth structure would have required a significant amount of high strength post-tensioning steel. Fig. 4 shows the final cross section adopted.

Cantilever construction with large equipment weights applied at the free end induces high compressive stresses in the bottom slab. This in combination with shear stresses resulting from the torsional moment and the longitudinal shear force, results in a bottom slab thicker than the usual 12 in. (305 mm) for the typical section and a web width of 18 in. (457 mm).

Through the use of Figg and Muller's exclusive Bridge Construction (BC) Program, it was possible to analyze the structure with a discrete model corresponding to the joints between segments (153 segments). Each stage of erection was analyzed. Stresses were checked at each segment placing, tendon stressing or support condition change. In addition, certain critical construction phases were analyzed, for instance, loads induced by trucks carrying segments over the completed deck.

The primary advantage of the BC program was its ability to handle long-term behavior computations. The time-dependent deformations were anticipated to be important because of creep, shrinkage and steel relaxation.

The long-term deformations calculated by the BC program have been found very consistent with actual measurements of deflections in the past. The accuracy was again verified with field measurements on Linn Cove. The program uses the FIP-CEB concrete creep provisions.

The transverse analysis was performed by utilizing the STRUDL program to analyze a three-dimensional fi-

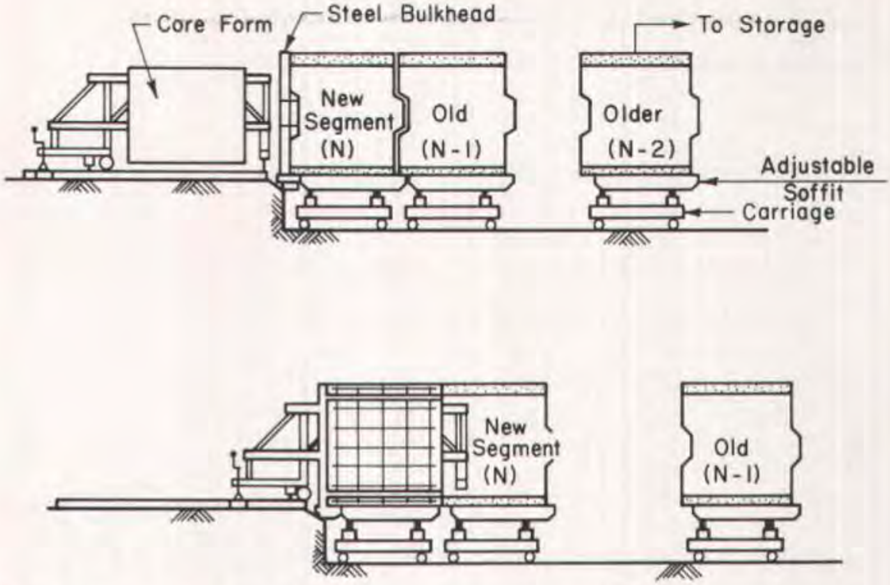

Fig. 5. Schematic of short line match-casting system as used on Linn Cove Viaduct.

nite element model. It should be recalled that Linn Cove was designed in 1978 and 1979. Figg and Muller has developed and now uses the much more powerful HERCULE program for three-dimensional finite element analysis.

The effects of the bridge horizontal curvature were analyzed using two additional three-dimensional computer programs:

- A curved beam program (ARC) to analyze the general behavior of the structure during construction and at service. This program allows the computation of load distribution in accordance with all element stiffness (box girder, bearings, piers and temporary supports).
- A finite element analysis program (TITUS) was used for the detailed design of torsional stresses in all members of the girder. In particular, this program was used to design the diaphragms (at piers and temporary supports) which transfer the torsional load to the bearings.

Torsional analysis was performed for all critical phases, i.e., completed cantilever with equipment loadings or deck behavior at temporary support removal.

CONSTRUCTION

Prior to discussing the precasting operation and erection sequence, some mention needs to be made about the contract administration of the project.

Contract Administration

The National Park Service (NPS) is the owner of the project and assumed overall responsibility. The NPS inspection responsibility related primarily to control of environmental aspects. Inspection was accomplished by periodic visits to the construction site. NPS personnel were also present at all construction meetings.

The Federal Highway Administration (FHWA) assumed responsibility for contract administration. A full-time staff on the construction site perfomed all inspection work involved with microshaft pile and footing construction. Superstructure and pier stem casting and erection were inspected with the assistance of Figg and Muller Engineers, Inc. The contractor for the project was Jasper Construction Company of Minneapolis, Minnesota. The contractor's successful bid on the project was $7.9 million.

Figg and Muller Engineers developed the original concept of the construction method. They also did the final design and prepared all contract documents. Because of the complexity of the project and relatively short time since the introduction of the segmental concept in the United States, the FHWA engaged Figg and Muller Engineers to provide the necessary segmental technical expertise to assure successful completion of the project.

The engineers served in strictly an advisory capacity to the FHWA, with no direct relation to either NPS or the contractor. All functions related to the specialized techniques required for segment casting and erection.

Segment Casting

To fit curvature and superelevation variation requirements, segments were laid out for the short cell method with match-cast joints. Each segment was cast in casting machines between a bulkhead and the previously cast segment. Fig. 5 shows the short cell match-cast arrangement where N-1 represents the match-cast segment and N, the segment being cast.

Horizontal curves, vertical curves and superelevations are obtained by adjusting the position of the match-cast segment. This procedure requires a special casting form designed to allow deformations between the bulkhead and the match-cast segment. Curves are accomplished by successive chords providing a slight angle change at each joint.

The precast pier segments were match-cast in the vertical direction as shown in Fig. 6. This method involved casting the new segment above the previously cast segment with steel forms used for the side forms and a core form to cast the void in the box. The reinforcing cages (including the vertical tendon ducts) were prefabricated.

The only geometry involved in casting the pier segments was the determination of the as-cast data and making minor corrections for casting variances. The as-cast data were later used when erecting the box pier segments.

The severe geometry requirements of Linn Cove necessitated some unique properties for the superstructure segment casting machine. The system had to be strong enough to support 55 tons (50 t) of concrete and steel; yet flexible enough to seal around the edges of the cast-against segment, which in some in-

Fig. 6. The box piers were cast with a vertical match-cast system. Here the cast-against segment is being prepared for casting its neighbor on top.

stances was severely skewed because of the large degree of curvature to be obtained.

To assist in obtaining adequate sealing to ensure smooth joints, the contractor installed a strip of rubberized material on the edge of the casting machine. This worked very well with the only detrimental effects being occasional pieces of rubber which would stick to the concrete. However, the pieces were easily removed. The casting machine is shown in Fig. 7.

The extreme weather conditions on Grandfather Mountain of below zero temperatures and winds ranging to 100 miles per hr (161 km/hr) influenced the contractor to enclose the casting machine and reinforcement cage fabrication area in a building. However, since the box pier segments were relatively few in number, they were cast outside.

Casting Geometry Control

The contractor had ultimate responsibility for the geometry control of the segments during the casting operation and during erection of the cantilevers. The contractor developed theoretical casting curves from the contract documents and submitted the data to the FHWA, which consulted Figg and Muller Engineers before giving approval.

The engineers established a completely independent geometry control system from that used by the contractor. The primary function of this separate evaluation was to provide a system of checks and balances, thereby assuring complete and accurate geometry control.

The three types of movement that can be required of a casting machine were

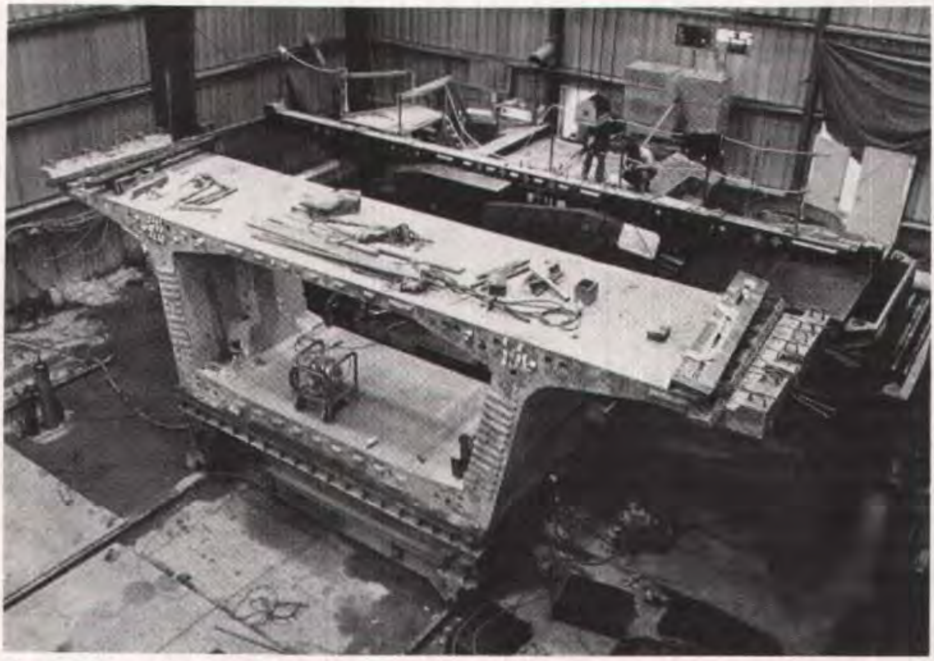

Fig. 7. The casting machine was located in a building enabling segments to be cast during the winter months. The next cast-against segment can be seen in the foreground; and, behind that, the steel bulkhead can be seen. The workers are standing on the core form which moves in to form the box girder void.

all required on this project, and to a much greater degree than on any previous bridge. They were:

- Movement in plane to obtain a curved alignment.
- Movement in elevation to obtain the desired vertical profile.
- A warping movement in the form soffit to obtain the desired cross fall variations.

The theoretical casting curves are those curves to which the segments are assembled in the bridge so that they will conform to the geometric shape shown on the contract drawings. The theoretical casting curves, therefore, have to take into account the geometric alignment and vertical profiles and the effect of the deflections in the superstructure that will occur during and after erection.

For a straight bridge, the casting curve is simply the same information on the contract drawings. However, in the case of Linn Cove, whenever any segment cast basically horizontal in the casting cell had to be rotated about its longitudinal axis to be placed in the bridge, the geometric profile of the segment and all its adjacent segments were very different to the alignment and profile shown on the contract drawings.

Normal geometry control procedures could not be used. The geometry of Linn Cove with 21 segments between cast-in-place closure joints would have resulted in the twenty-first segment being approximately 4 in. (102 mm) off line and 6 ft (1.8 m) off grade, had not the bridge and casting cell angular change differential been taken into account.

For bridges of larger radii and 3 percent superelevation, the effect is insignificant in alignment, but not profile. For this bridge, it was necessary to generate "geometry" casting curves from "global" data on the contract drawings by transformation to the local "casting cell" axis.

Fig. 8. The contractor chose to erect the segments with this stiffleg crane attached to the end of the cantilever. This single piece of equipment controlled the construction rate of the bridge. All material and equipment was handled with this crane.

Segmental Box Pier Construction

All pier footings are 20 ft (6.1 m) in diameter and 5 ft (1.5 m) in thickness. The footings are founded on variable thickness nonreinforced subfootings through which microshaft piles were drilled.

After forming the footings and placing

Fig. 9. Precast box pier segments were lowered over the end of the completed cantilever with the stiffleg. The workmen are ready to block the segment and apply the epoxy.

the reinforcement and post-tensioning conduits, the first of the precast segments was placed. A steel frame fabricated from rolled sections was placed in the footing simultaneously with the reinforcing bars. The frame provided support for the first box pier segments.

The initial precast segment was placed on shims and flat jacks which enabled proper alignment. The segment had to be aligned to correct for casting variations and actual superstructure position. Movements were achieved by pumping the flat jacks one at a time or in combination. The segment was supported at four points.

The contractor was responsible for aligning the segment and the alignment was subsequently verified by the engineers. After verification, the footing was cast. The top of the footing extended approximately 1 in. (25 mm) above the bottom of the segment and the support beams for the segment were lost.

After the footing concrete had hardened, the joint between the cast-in-place concrete and the precast segment was pressure grouted with epoxy. The purpose of the epoxy was to waterproof the joint. The epoxy was not related to strength. The precast box pier segments were delivered over the completed portion of the superstructure which extended to within two segments of the pier location. The segments were lifted over the end of the cantilever by a stiffleg crane attached to the cantilever (see Fig. 8).

Fig. 9 shows a box pier segment being lowered. The pier segments were blocked about 6 in. (152 mm) above the previous segment while epoxy was applied. The segment was then lowered to the face of its match-cast unit where thread bar tendons were installed and stressed. Each pair of segments were stressed together with thread bars. The process was repeated until all of the hollow segments were erected and the pier was ready for the cap.

The last step in the pier construction was to place the cap and stress eight 12-strand tendons. These tendons extend from the top of the pier down through and out the side of the footings. Once stressing was completed, the tendons were grouted.

Superstructure Segment Erection

Superstructure segments were delivered to the end of the cantilever by a low-boy tractor trailer (see Fig. 10). Because of the limited access, the truck had to be backed up the access road and backed out onto the completed portion of the bridge.

The crane which lifted the segments from the truck and swung them around to the end of the cantilever was an American S-20 stiffleg crane. It was equipped with a 70 ft (21 m) boom and provided a 125 kip (556 kn) lifting capacity at a 25 ft (7.6 m) boom radius.

The crane had to be moved forward after each segment was erected. Generally, it was located two segments behind the segment being erected. The moving operation involved lifting the entire assembly, removing the steel support beams and lowering the assembly onto steel rollers. Once the crane was supported on rollers, it was pulled forward by hand-operated winches. Then the lifting process was reversed. The steel support beams were reinstalled and the crane was tied down.

The moving operation cycle took 4 to 6 hours to complete. Moving the stiffleg crane entirely controlled the erection rate of superstructure segments. Incorporation of a swivel crane as detailed on the contract drawings or modifying the stiffleg crane for faster moving would have substantially increased the superstructure erection rate.

The following is a step-by-step procedure followed during the erection of a typical segment:

Step 1 — The segment was backed to the end of the bridge by truck (see Fig. 10).

Step 2 — The stressing cages were picked up by the stiffleg and attached to the new segment (see Fig. 11).

Step 3 — The lifting spreader beam was lifted with the stiffleg and the lifting cables attached to the new segment.

Step 4 — The segment was lifted to clear the trailer and the slope was checked to see that it matched the degree of superelevation at the end of the cantilever. If necessary, it was adjusted.

Step 5 — The segment was lifted by the stiffleg, swung around and lowered

Fig. 10. 50 ton (45 t) segments had to be backed for distances exceeding 1 mile (1.6 km) in many instances because there was insufficient room to turn this rig around.

Fig. 11. The first step in the erection sequence was to remove the post-tensioning stressing cage from the end of the cantilever. The permanent tendon live end anchors can be seen at the top of the webs.

to within about 6 in. (152 mm) of the end of the cantilever (see Figs. 12, 13, 14 and 15).

Step 6 — The segment was pulled horizontally to the end of the cantilever with cable winches and blocked 6 in.

Fig. 12. The segment was lifted from the truck on the right and swung out over the cantilever end.

Fig. 13. Then the segment was lowered vertically.

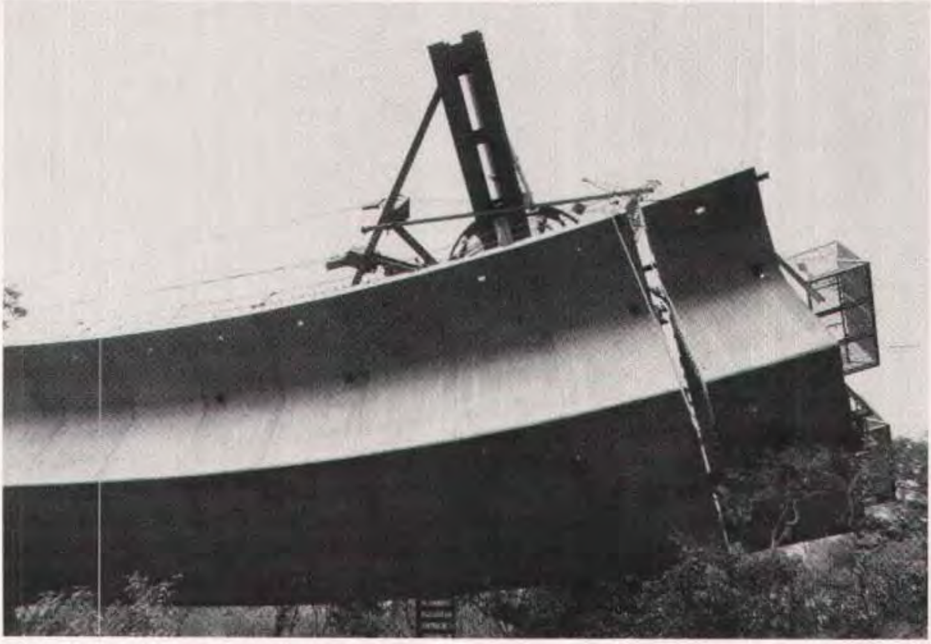

Fig. 14. Here the segment is in place ready to receive the epoxy bonding agent. The excellent fit of the previous joints and the curvature can be seen. Most joints were less than 1 mm (0.004 in.) in thickness.

(152 mm) away with wood blocks. It was still supported vertically by the stiffleg.

Step 7 — The temporary thread bar tendons were threaded and the nuts finger tightened.

Step 8 — The epoxy was mixed and applied.

Step 9 — The wooden blocks were removed and the segment closed to the end of the cantilevers with the cable winches.

Step 10 — The temporary thread bars were stressed.

Step 11 — The permanent 19-strand tendons were threaded and stressed.

Step 12 — The temporary thread bar tendons were released.

Because erection of the superstructure continued through the winter, provisions were taken to heat and insulate the joints of the precast segments. In particular, measures were taken to be sure the epoxy in the joints was heated

Fig. 15. Erection progress (May 20, 1982).

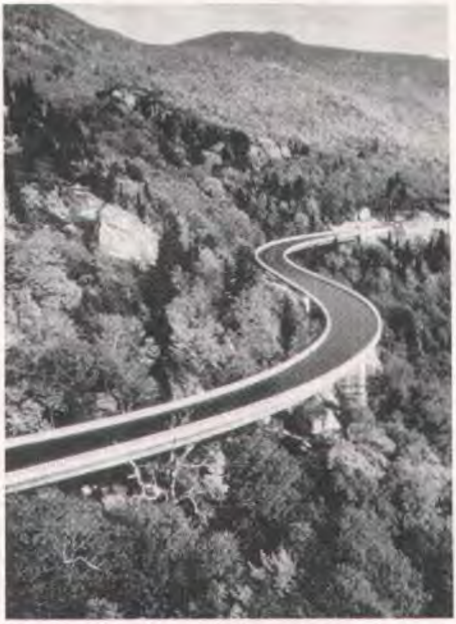

Fig. 16. Linn Cove Viaduct winding through the Blue Ridge Mountains.

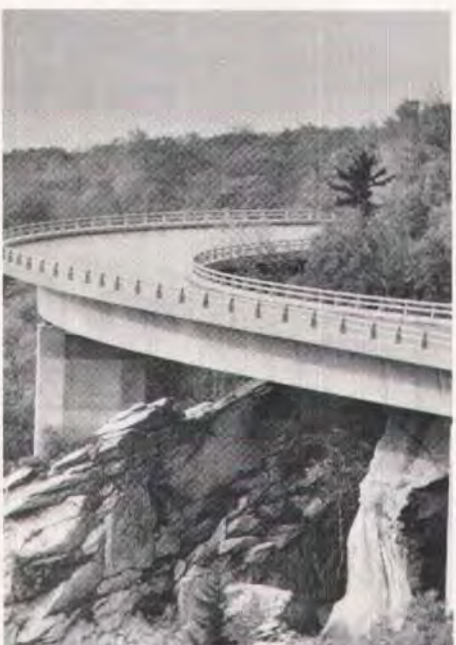

Fig. 17. Closeup of one of the many turns of the bridge.

to at least 40°F (4.4°C) in order for the material to cure properly. Prior to construction, an elaborate testing program was undertaken to make sure that the heating/insulating system worked properly. For more details, see the article listed below.*

Erection Geometry Control

Figg and Muller's responsibility for erection geometry control was to advise the FHWA of the bridge's relative position to the plan and profile grade lines. The responsibility included verification of the positioning of bent segments by the contractor prior to casting closure joints and the positioning of the bottom pier shaft segments.

During erection, the bridge was tracked using the survey control points cast into the top slab of the segments. The expected erection grades were predetermined at each stage of construction for the three leading joints of the cantilever. These grades consisted of a summation of the desired final grade, the as-cast variances and the cantilever camber data. The actual elevations of the joints were plotted on graphs for comparison with expected elevations.

It was determined early in the erection that the bridge was moving too much to acccomplish accurate horizontal tracking with the instrument on the bridge. The theoretical horizontal position of the cantilever end was determined by calculating coordinates from the base grid on the plans. The actual coordinates of the cantilever end were determined by turning angles and measuring distances from known points.

The specified erection tolerance was ±1 in. (25 mm) in both the vertical and horizontal directions. An early decision was made that with the many adjust-

* Muller, Jean, and Barker, James M., "Joint Heating Allows Winter Construction on Linn Cove Viaduct," PCI JOURNAL, V. 27, No. 5, September-October 1982, pp. 120-130.

ments available at closure joints and aligning box pier segments, there would be no need to shim the segments. Shimming was only to be used when no other way out could be foreseen, and with this type of erection there was always another way out. Shims were never used.

The 250 ft (76.2 m) radius curves, spiral curves, and many superelevation transitions were negotiated without a significant problem. The rigid controls exercised during casting made the erection process very smooth.

The last segment was placed on December 22, 1982. During 1983, the contaractor cast the curbs, completed the last abutment, finished the grade on the north end of the viaduct (inaccessible before the bridge was erected), installed guardrails and applied the waterproofing membrane and wearing surface.

The bridge was completed without a single structural problem. There is not a crack in any of the precast superstructure or substructure segments. The project is a tribute to what can be accomplished with proper segmental design and construction techniques. Figs. 16 and 17 show the completed bridge.

CONCLUDING REMARKS

The Linn Cove Viaduct is a vital part of the missing link of the Blue Ridge Parkway. Connecting roadways will complete that link by 1987, allowing the general public access to an award winning example of engineering ingenuity: A truly innovative bridge by design, built under difficult conditions, and set in complete harmony with its natural surroundings. Attesting to its success, the project has won eight national design awards including a PCI Awards Program winner in 1983.

CREDITS

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Foundation Design/Construction Administration: Federal Highway Administration, Eastern Division, Direct Federal Projects, Arlington, Virginia.

General Contractor: Jasper Construction, Inc., Plymouth, Minnesota.

Owner: National Park Service, Denver, Colorado.

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